Special Study Group 1.158:
GPS Antenna and Site Effects

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1 Introduction

During the last few years, an increasing number of permanent GPS sites have been established. The demonstrated repeatability of horizontal position estimates for regional networks is currently of the order of 2 mm and typically a factor of 3-5 greater for the vertical component. There are many advantages to continuously operating GPS networks. Stable pillars with fixed antennas eliminate errors associated with variations in the measurement of the local vector from the reference marker to the phase reference point of the antenna. For fixed pillars in a continuously operating network, the reference marker is usually a fixed, well-defined point on the antenna. In addition, denser position estimates (spatially and temporally) decrease the statistical uncertainty of the results. Continuously operating networks may also serve as a global or regional reference frame for different types of regional and local surveys. Another essential advantage is the increased ability to study and eliminate unmodeled systematic effects on daily estimates of site positions, both short- and long-term effects.

To be able to constrain the common mode of motion, sometimes in the sub-millimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a high degree of robustness. In addition, orbits must be compatible with the reference frame. Site-specific errors at permanent stations may introduce errors in the determination of satellite orbit parameters and in the estimate of site positions. In the following we address the problem of site-specific errors and present some recommendations on how to handle these errors.

2 Objectives

The objectives of SSG 1.158 were to:

1. investigate the characteristics of different GPS antennas (mainly those used in high-precision applications) based on measurements in anechoic chambers, field experiments, and numerical evaluation; study the effects of "antenna mixing"; design and evaluate new GPS antennas;

1. study the influence of electromagnetic scattering (including multipath) and provide information on how to minimize these effects;
2. investigate and formulate recommendations regarding establishment of new GPS sites, including the design and construction of pillars (monuments) and the monitoring of their long-term stability; evaluate radomes used to protect permanently installed antennas;
3. study and minimize the influence of snow, rain, and local atmospheric conditions on the final estimates; provide information and recommendations on how to eliminate (or minimize) the effects of radio interference.

3 List of Members

Jan Johansson (Sweden), James Campbell (Germany), Thomas Clark(USA), James Davis(USA),Charles Dunn (USA), Alain Geiger (Switzerland), Kenneth Jaldehag (Sweden), Hannu Koivula (Finland), Richard Langley (Canada), Kristine Larson (USA), Gerry Mader (USA), Chuck Meertens (USA), Peter Morgan (Australia), Antonio Rius (Spain), Markus Rothacher (Switzerland), Bruce Schupler (USA), James Tranquilla (Canada), Danny Van Loon (The Netherlands), Luca Vittuari (Italy), Rene Warnant (Belgium)

4 Corresponding members

Geoffrey Blewitt (UK), Beat Burki (Switzerland), Ulf Lindqwister (USA), Sammy Musyoka(Germany/Kenya), Chris Rizos (Australia), Wolgang Schlueter (Germany), Hiromichi Tsuji (Japan, Arthur Niell (USA), Tom Herring (USA)

5 Meetings

Discussions and special sessions have been organized at meetings such as of the American Geophysical Unions (AGU), The European Geophysical Society (EGS), International GPS Service (IGS), and IAG.

6 Work

Site Specific Errors

We have chosen to divide the site specific error sources into three subgroups. The first group consists of problems associated with the receiver, antenna, radome, and the signal. These are effects that will not, in general, change on a day-to-day basis. However, they might introduce biases in the solution. As long as nothing changes the effect stays the same. If something changes, such as the satellite constellation or the elevation cut-off angle, the results will be affected.

The influence is especially obvious looking at the estimates of the vertical components and precipitable water vapor where bias terms can be introduced (*Elòsegui et al*. 1995; *Niell et al*., 1994; *Niell*, 1995). Such a bias could seriously affect the interpretation of the GPS data. The second group represents areas of site effects that will vary, but will only periodically affect the measurements. Precipitation, multipath, atmospheric pressure loading, and atmospheric gradients are probably the most important of these, but others may be discovered.

Finally, the third group consists of errors that might affect the long-term stability of a site such as the location of the site, ground, and the monument. Most of the material related to this specific group of site errors are rather new. These errors may seriously affect the reference frame and the geodynamical projects.

GPS Antennas

It has been found that antenna-to-antenna phase differences can introduce range biases at the several centimeter level, which may limit the precision of the measurements *Rocken* (1992). Differential phase errors due to GPS antennas will not only affect the precision in GPS networks with different types of antennas, but also in networks using identical antennas if the network covers a large spatial area (baseline lengths ~1000 km) (*Schupler and Clark* 1991*; Schupler et al*. 1994). Differential phase errors in regional networks (baseline lengths ~1000 km) using identical antennas are dependent on the electromagnetic environment around each individual antenna.

The problem of antenna mixing was addressed at the IGS Analysis Center Workshop in Silver Spring, 1996. Two sets of phase calibration corrections (PCC) tables have been put together based on material presented *by Mader and MacKay* (1996), *Rothacher and Schär* (1996), and *Meertens et al*. (1996a) to be used by the IGS Analysis Centers and others in the GPS community: (1) a set of "mean" phase center offsets and (2) a set of elevation-dependent PCC and offsets relative to the Dorne Margolin T antenna.

Since the PCC values are all relative to the Dorne Margolin T antenna some effects of antenna mixing still remain. Even with the same type of antenna the variation in the apparent phase center as a function of elevation angle will influence the results on longer baselines. Therefore the task of getting absolute calibration of the antennas through, e.g., chamber measurements or simulation software may be essential for some applications even though these calibration values most likely will change when the antenna is deployed in the field. Effects like these can of course be reduced by utilizing antennas less sensitive to scattering from external structures. One way to achieve this is to reduce the side- and back-lobe levels of the amplitude patterns by means of well designed ground-planes. For this purpose new antenna designs have been proposed (see e.g., *Alber*, 1996; *Ware et al.,* 1997; *Jaldehag et al*. 1995; and *Clark et al*. 1996). Furthermore, several groups are currently developing methods to perform absolute field calibration of antennas (*Wubbena* et al., 1996; *Elòsegui et al*., 1999) and in-situ calibration of antenna/pillar systems.

Antenna-Pillar System and the Signal

Here we concentrate on the site-dependent error associated with the electromagnetic coupling between the antenna and its nearby environment (*Tranquilla*, 1986; *Tranquilla and Colpitts*, 1988). The total electromagnetic field of an antenna which radiates a signal in the presence of conducting structures may be expressed as a superposition of the transmitted field and the fields scattered (i.e., reflected and diffracted) by the structures. By reciprocity, the same is true for a receiving antenna. The significance of the scattered field depends on the degree of electromagnetic coupling between the antenna and the scatterer, that is, the distance to the scatterer and the size and reflectivity of the scatterer. Signal scattering affects both the amplitude and phase of the received GPS signal, presumably independently at each site in a network. This independence creates differential phase errors.

Scattering from structures in the vicinity of the antenna effectively changes the antenna phase pattern, and, thus, affects the precision of the carrier phase measurements of the GPS signal. In studies by *Elòsegui et al*. (1995) *and Jaldehag et al*. (1996a) it was shown that estimates of the vertical component of baselines formed between sites using identical antennas were dependent on the minimum elevation angle of the data processed. Both studies found that the elevation-angle-dependent systematic effect was associated with non-identical pillar arrangements, causing differential phase errors due to scattering from structures associated with the mounting of the antenna to the pillar, and with the pillar itself. Even the most perfectly calibrated antenna the antenna phase pattern will change when attached to a pillar.

Jaldehag et al. (1996a) demonstrate that estimates of the vertical component of many baselines strongly depend on the minimum elevation angle (elevation cutoff angle) of the data analyzed. A significant part was found to be due to differential phase errors caused by scattering from structures associated with the mounting of the antenna to the pillar and with the pillar itself. As the precision and accuracy of GPS measurements improve in general, antenna phase pattern variations due to different pillars and antenna mounts could be the major error source in just a few years, if not now. Modeling of the scattering effect, or rather the complete phase response of the antenna system, including the pillar, is an important issue for future improvements of the GPS technique.

Radomes - Protective Covers

At several permanent GPS sites located in areas with periodically severe environmental conditions (snow, rain) radomes have been employed. Until recently, most radomes in use have had a conical shape. All materials have some effect on a electromagnetic wave. Radomes appear to delay and refract the GPS-signal in a similar way as snow *Jaldehag et al*. (1996b). Several groups have recently been investigating effects due to the excess signal path delay through the radome. Different radomes have been tested in anechoic chambers *Clark et al*. (1996); *Meertens et al*. (1996b) as well as in field tests *Meertens et al*. (1996b); *Jaldehag et al*. (1996c). All tests show that a conical cover may cause cm-level vertical errors when the tropospheric delay parameter is estimated. The recently employed hemispheric radomes seems to show much less elevation dependence. The influence on the tropospheric wet delay estimates and subsequently, the vertical component will only be on the 1-2 mm level. We can conclude that all radomes effect the GPS signal at some level and in form of an excess signal path delay which will map into other parameters in the GPS software. The effect of the protective covers can most likely be misinterpreted as a tropospheric effect in a similar way as snow. The effect is more or less constant and may be calibrated or modeled.

Precipitation

Signal propagation delay during snow storms has been investigated by, e.g., *Tranquilla and Al-Rizzo* (1993) and *Tranquilla et al.* (1994) who demonstrated that due to the localized nature of many snow storms differential effects may cause systematic variations at the centimeter level in estimates of the vertical coordinate of site position. Systematic variations introduced by snow storms may, however, if short-lived (minutes to hours), be reduced to a high degree by data averaging. A potentially more serious effect of heavy snow precipitation is the accumulation of snow on the top of the GPS antenna and on its surroundings, such as on the top of the GPS pillar or, when present, on the radome covering the antenna. This accumulation may last for days, weeks, or months. *Webb et al.* (1995) reported variations on the order of 0.4 m in estimates of the vertical coordinate of site position. The variations were correlated with the accumulation of snow over the antenna. Variations at the several centimeter level in estimates of the vertical coordinate of site position strongly correlated with changes in the accumulation of snow on top of GPS antennas have also been observed by others *Jaldehag et al.* (1996b); *BIFROST project members* (1996); *Meertens et al.* (1996a). The results indicate that the variations in the vertical coordinate of site position can be fully explained by reasonable accumulations of snow which retard the GPS signals and enhance signal scattering effects.

Horizontal Atmospheric Gradients and Air Pressure Loading Effects

In the data processing the atmosphere is normally considered to be spherically stratified. We assume that one equivalent zenith wet delay value determines the wet delay in any direction, given a certain elevation angle. More advanced models, using more parameters to describe the atmosphere, have been proposed as alternatives to this very simplified model (*Davis et al*., 1993; *Macmillan,* 1995). Several groups are now implementing possibilities to estimate horizontal gradients in the software *Bar-Sever and Kroger* (1996); *Chen and Herring* (1996).

The lack of pressure data available during the GPS analysis can be the reason for different errors. During the entire GPS processing we have to model many external and internal effects on the crust of the earth. One effect currently not modeled is the pressure loading. The vertical position of the GPS receiver changes due to different atmospheric pressure loading the Earth (*vanDam and Herring*, 1994). Extreme values could affect the vertical component of the GPS estimates on the cm level. These effects are of course related more to the general pressure field in the region rather than to a specific site. To properly model this effect a grid of pressure data has to be available. Unfortunately, it is very difficult to isolate these effects from other elevation-angle-dependent effects (multipath, scattering, snow/ice etc.). Small variations in the vertical component are also caused by these other errors. We are thus not in the position of being able to correct for horizontal atmospheric gradients and loading errors optimally. At this point, theoretical studies are needed to quantify these effects, and to understand how we can best deal with these problems.

Local Stability and Monumentation

As GPS measurements have become more precise and are more frequently acquired, the issue of monumentation and site stability has become more important. The long-term contribution to the maintenance and densification of the global reference frame could be seriously affected by unstable sites. The IGS network consists of a large variety of monuments established on top of everything from solid bedrock to buildings. The long-term stability of the reference frame and products associated with it, such as the orbits, are at issue here. Much attention is currently focused towards motions of geodetic monuments. These motions have been found by some researchers to be random-walk-like (e.g. *Johnson et al*., 1995; *Johnson et al.,* 1996) while others find no evidence for random walk behavior (e.g. *Mao et al*., 1996; *Davis et al*., 1996). An ideal GPS monument would move in response only to the tectonic motion of the Earth. However, location, ground, and the environment at ground surface can have dramatic impact on the long-term stability of a site. The implication of this type of power-law noise is serious if the data are used to estimate low-frequency characteristics of a time series such as the slope (deformation rate). *Mao et all* (1996) and *Davis et al*. (1996) found no tendency of a random-walk like behavior possibly because the records where not long enough to see a random walk component above the noise in the low portion of the signal. It is also quite possible that monument motion may depend critically on the monument design and the site locations.

Nevertheless these investigations will continue and are most effectively addressed using continuous GPS measurements gathering data in a large variety of local conditions and GPS satellite configurations. There are design techniques that can be employed to mitigate this unwanted influence, most of which involve anchoring the monument to several points at depth and isolating the monument from surface material. Detailed spectral analyses and examination of the long time series available for some of the global sites. Monument and local stability problems could also manifest themselves with a periodic behavior, and be correlated with atmospheric conditions and precipitation.

7 Conclusion and Recommendations

Site-specific errors cannot be separated out when data from permanent sites are being used to determine orbits and reference frame. To be able to constrain the common mode of motion, sometimes in the sub-millimeter range, in a regional or local network a strong reference network is needed. The origin of the reference frame must be maintained with a high degree of robustness. In addition, orbits must be compatible with the reference frame. For this purpose the permanent sites need to be better examined. We especially found that the problems associated with the antenna-pillar system and the signal distortions have to be addressed. The effect of the antenna and signal related errors are constant from day-to-day but are biasing products like the orbit determination, station time series, and precipitable water vapor time series. Any changes either at a station or in the GPS-data analysis strategy might change this bias and thereby affect the daily products and the reference frame. The other important issue that needs attention is the long-term stability of the sites and the monuments. This is especially important bearing in mind that local and regional continuously operating GPS networks are now used to detect motion at the level of 1 mm/yr or less.

A list of recommendations have been compiled. Most of the items are related to permanent stations which has been the main focus of the studies. Many of the recommendation will also have implications in campaign type of measurement if high-precision results should be obtained.

- Use Calibrated and well-known antennas
- Avoid pillar-scattering and multipath
- If possible, calibrate antenna/pillar
- If radome, use hemispheric type
- For time-transfer purposes (and more??) keep hardware in a temperature controlled environment
- Long-term stability of site and monument
- Low elevation data, atmospheric gradients and atmospheric loading needs further investigations

8 Future Work

GPS/GLONASS receiver systems and site effects are important error sources. The individual members of the SSG 1.158 have contributed to the increased awareness of problems associated with GPS antennas and site effects. The work must continue to push current limits of navigation satellite systems development in hardware and software (both satellites and receivers). A new IAG SSG are being established. Similar activities are also being organized in many countries.

9 Some Web Sites

www.grdl.noaa.gov/GRD/GPS/Projects/ANTCAL/

.igscb.jpl.nasa.gov

www.oma.be/KSB-ORB/EUREF/eurefhome.html

www.unavco.ucar.edu

www.cx.unibe.ch/aiub

www.unb.ca/GGE/personnel/Langley/Langley.html

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